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LASER-DRIVEN MINIFLYER INDUCED GOLD SPALL

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Abstract. A laser-launched minature flyer system (called MiniFlyer) is being used to study the dynamic properties of materials. The flyer plates are typically 3-mm diameter and less than 0.1-mm thick. The flyer is accelerated by a laser-pulse-induced plasma contained by a clear window substrate and the flyer plate attached to it. The substrate is coated (by chemical vapor deposition) with carbon, aluminum oxide, and aluminum to enhance the laser deposition/plasma formation process. After traveling through a barrel about 3 to 5 flyer thicknesses long, the flyer impacts a target plate, producing a shock pulse imput to the target material. In this study the target was a gold foil with a free back surface. Gold foils with thicknesses between 0.1 and 0.26 mm were used. When the shock pulse interacted with the free surface and reflected as a rarefaction wave, tension was produced in the foil generating a spall. Dynamic measurements of the free surface particle velocity were made using VISAR (Velocity Interferometry System for Any Reflector). Since the flyer and target are easily recovered in these experiments, the target was cross sectioned to reveal the position and nature of the spall.

INTRODUCTION

Spall experiments on materials which are measured on micron scales compliment traditional spall measurement techniques where material dimensions are orders of magnitude larger. In general, scaling down the size of experiments will not significantly alter the results. However, there are limits. These are associated with the resolution capabilities of the diagnostics, the strain rate, and grain size.

A number of laser generated shock studies utilizing micron scale samples have been reported in which sufficient resolution is achieved by optically recording data on streak cameras.[1-3] Additionally laser based techniques have exploited the strain rate dependence to extend the spall strength as a function of strain rate and validate theoretical models.[1,2,4] Concerns associated with grain size are simply related to the numbers of grains sampled in an experiment, e.g. experiments where the foil thickness approaches the grain size. Experiments such as these could reveal properties different from traditional techniques which average out such effects by using thick samples. However, this is a complimentary aspect of small sample experiments allowing limited quantity materials, such as single crystals to be tested.

In this study a single shot laser is used to launch 50 μm copper flyers into gold targets of two thicknesses, 0.1 and 0.26 mm. In these experiments traditional PMT based VISARs were sufficient to resolve pertinent features in the velocity profiles. Similar MiniFlyer spall data on copper and aluminum has been reported by Paisley et. al.[3,5]

EXPERIMENTAL

A brief description of the experimental apparatus as well as an explanation of the flyer velocity-laser

energy relationship is given in another paper in these proceedings by the same authors and only a minimum of supplemental expermental information follows.

Copper (0.05 mm OFHC at 99.95+%, Goodfellow Corporation, PA, USA) was used as the flyer material for these experiments. Gold targets were purchased from two different sources: 1) 0.10 mm gold foil at 99.99+% from Goodfellow Corporation and 2) 0.1 mm and 0.25 mm gold foil at 99.95% from Alfa Aesar MA, USA.

The gold was used as received except for mild surface roughening to minimize specular reflection being input into the VISAR.

Dual VISARs (Valyn International, NM, USA, model VLNV-04) were used for these experiments for added confidence in the addition of lost fringes.

The flight path was controlled by placing a spacer (0.125 to 0.185 mm) between the substrate window and the impact window (figure 1) yielding a total flight path of 0.075 to 0.125mm.
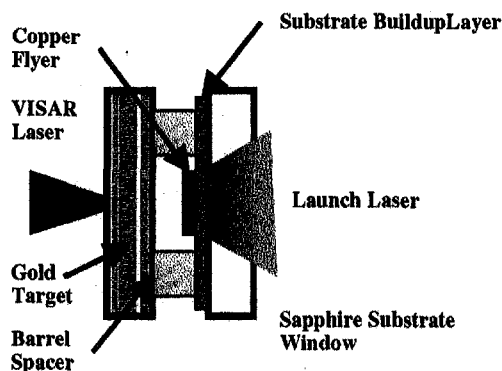
FIGURE 1 Schematic of gold spall experimnts for 0.05 mm copper flyer and 0.1 mm gold target.

RESULTS

Approximately 15 spall experiments were completed for gold targets of 0.1 mm thickness with copper flyers (0.05 mm thick) varying in velocity. The velocity profiles (figure 2a) for each of these shots exhibits a fast rise to a maximum, which ranged from 100 to 250 m/s. Velocity profiles marked by sharp pull back signals approximately 20 ns after first movement and a re-acceleration are attributed to spall in the gold target.

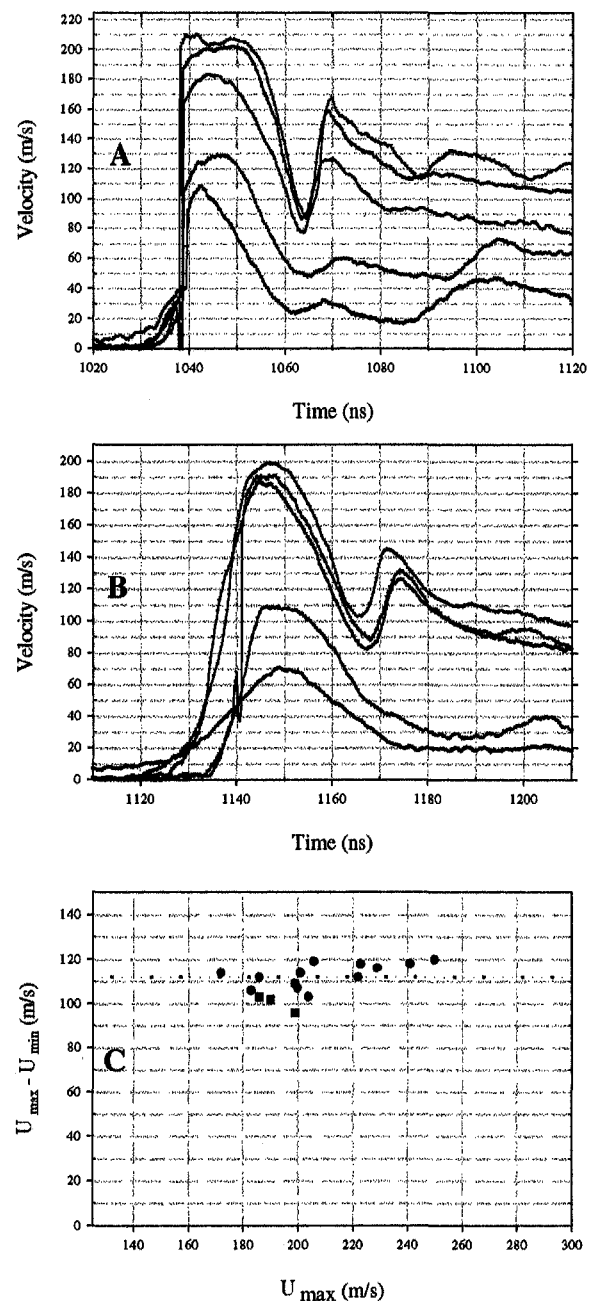The lowest peak velocity for these spall signals was 172 m/s.

FIGURE 2 A)Gold (0.10 mm) spall velocity profiles, B)Gold (0.26 mm) spall velocity profiles, C) Experimentally measured velocity differences U_{max} - U_{min}. Thirteen circles correspond to 0.10 mm gold and the three squares to 0.26 mm gold targets.

An analytical method[6] was used to estimate the spall strength from thirteen of these shots. The method is based on the difference between the peak velocity, U_{max}, and the first minimum, U_{min}, in the velocity profile. The spread in velocity difference, $U_{max} - U_{min}$, is shown in figure 2c and yields an average of 113 m/s with a standard deviation, S_x, of 5.4 m/s. Using this value in equation 1, where Z is the product of the initial density and the wave speed, we obtain a spall strength of 3.3 Gpa.

$$P_{spall} = 0.5\, Z\, (U_{max} - U_{min}), \qquad \text{Eq. 1}$$

Two of the shots, shown in Figure 2a, achieved a maximum velocity less than 130 m/s and appear significantly different from those at higher energies. For these cases, it appears the peak tensile stress was insufficient to spall the gold target.

Five spall experiments were completed with gold targets of approximately 0.26 mm. As before 0.05 mm copper flyers were used as impactors. Results of these five tests are shown in Figure 2c. Three of the profiles show spall signatures similar to those observed for the 0.1 mm gold. The average $U_{max} - U_{min}$ for these three shots is 100 m/s ($S_x = 3.8$ m/s) yielding a spall strength of 3.0 Gpa. The remaining two shots attained a maximum velocity less than 120 m/s and do not exhibit the characteristic spall profile, consistent with similar shots for the 0.1 mm gold targets.

In general the pull back signals have a break in their slope over half way to U_{min}, with the lower half falling faster. However, we averaged the two slopes for four of the pull back signals and obtained a slope of -9.99 m/s/ns, ($S_x = 2.1$), for the 0.10 mm gold. A strain rate of 1.6×10^6 s^{-1} is calculated with the slope, du/dt, and sound speed, C_0, using equation 2.[7]

$$\acute{\varepsilon} = - \, du/dt \, / \, 2\, C_0 \qquad \text{Eq. 2}$$

Slopes for the 0.26 mm gold are qualitatively similar but have a lower average slope, -6.16 m/s/ns ($S_x = 0.67$). Using equation 2 again, we obtain a strain rate of 1.0×10^6 s^{-1}.

For these MiniFlyer experiments, both the flyer and spall target are easily recovered and several of the targets have been cross-sectioned. For 0.10 mm gold spall shots, where U_{max} exceeded 200 m/s,

spall was immediately noticeable, i.e. without cross-sectioning. For many of these the spall layer became completely detached (figure 3a). Course measurements of these spalled sections show the spall to have occurred approximately 55 microns into the gold target from the impact side. Other targets required cross-sectioning to reveal the spall (figure 3b).

The only external indication of spall on the 0.26 mm gold targets were irregularities on the target opposite the impact side. Spall was verified in these targets by cross-sectioning. A cross-section revealed the spall to have occured at approximately 200 microns in the gold from the impact side.

FIGURE 3 a) Cross-section of 0.10 mm gold target. B) Photograph of gold target (0.10 mm) opposite impact side. Detached region is approximately 2 mm in diameter.

DISCUSSION

We have not modeled these experiments, but have used existing hugoniot data to check for qualitative agreement. A t-x diagram (time versus distance) cartoon of the experiment is shown in figure 4. At time 0 shock waves (solid lines) begin traveling both into the copper and gold. The shock wave in copper is the first to reach the free surface and a right going rarefaction wave (dashed lines) begins traveling in the same direction as the initial

shock in the gold target. Upon encountering the copper-gold interface the rarefaction continues in the gold, but at a different velocity. At this point the copper flyer separates from the gold and waves continue to oscillate between the two free surfaces of the copper flyer, but have no additional effect on the gold spall. At 30 ns the shock wave in gold has reached the free surface and generates the first observed motion in the velocity profile. A left going rarefaction fan is generated and interacts with the right going rarefaction at about 43 ns generating tensile stress at about 0.06 mm into the gold, agreeing well with the spall location in the 0.10 mm gold targets. A similar analysis for the 0.26 mm gold targets indicates the position of peak tensile stress at 0.22 mm, which also compares favorably with the experimentally measured spall at 0.20 mm.
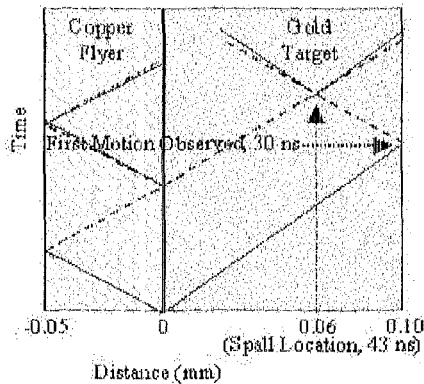

FIGURE 4 T-X diagram for a 0.05 mm copper flyer impacting a 0.100 mm gold target.

The average copper flyer velocity in this work is 0.3 km/s which generates a particle velocity of 0.11 km/s and a pressure of 7 Gpa. Based on this, the expected velocity measured at the free surface will be about 0.22 km/s and remain constant for approximately 20 ns, which is in agreement with the measured velocity profiles for the 0.1 mm gold.

A simple approximation to the theoretical spall strength is the bulk modulus ($B_0 = 171$ Gpa) divided by π, which yields a pressure of 50 Gpa. Equation 3 is an estimate which incorporates the bulk modulus and cohesive energy ($E_{Coh} = 1.75 \times 10^6$ J/kg). The theoretical spall strength[6] calculated with this method is 27 Gpa.

$$P_{Th} = \sqrt{(B_0 E_{Coh} \rho / 8)} \quad \text{Eq. 3}$$

As expected, these values for spall strength are significantly higher than that obtained experimentally. Ductile spall is believed to initiate through void nucleation, growth and coalescence, which the above expressions for theoretical spall strength do not consider. Furthermore, the spall strength has been shown to have a dependence upon the strain rate, i.e. at low strain rates there is a sufficient amount of time for growth and coalescence of voids. However, as the strain rate increases, the amount of time available for growth and coalescence becomes too short, so new voids must be created, which increases the spall strength. Dekel et. al. have shown a dramatic increase in the spall strength for copper and aluminum at strain rates of 10^7 s^{-1}.

CONCLUSIONS

Spall strength was determined to be 3.3 and 3.0 Gpa for 0.1 and 0.26 mm thick gold samples. This value is well below the theoretical spall strength and above the reported yield strength for gold, 0.139 Gpa.[8] Strain rates were estimated as 1.6×10^6 and 1.0×10^6 s^{-1} for the 0.1 and 0.26 mm targets respectively.

Spall was not observed for either gold thickness when the gold free surface velocity, U_{max} was less than 130 m/s. The lowest free surface velocity measured at which spall did occur was 172 m/s for a 0.10 mm gold target.

Easy recovery afforded by this technique allowed verification of our spall analysis. However, we have not satisfactorily examined the targets for which we believe spall did not occur. Additional shots near the spall threshold, as well as post-shot analysis for incipient damage will be completed at a later date.

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